ENHANCEMENT OF OCCUPANT SAFETY IN OFFSET FRONTAL VEHICLE COLLISION: USING NOVEL MATHEMATICAL MODELLING ALONGSIDE VEHICLE DYNAMICS CONTROL SYSTEMS

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15-0409

ABSTRACT

Occupant safety is one of the most important issues for vehicle manufacturing. Active safety plays an important role to protect the occupant during the crash events. In this paper, vehicle dynamics control systems (VDCS) are used to enhance the occupant safety in offset frontal vehicle collision. VDCS are activated to optimize the vehicle in impending collision. A new mathematical modelling of the vehicle alongside VDCS is developed to study the effect of vehicle dynamics control systems on vehicle collision mitigation. A multi -body occupant mathematical model is developed to capture the occupant kinematics during frontal offset collision. Different cases of vehicle dynamics control systems have been used to show their effect on the occupant dynamic response. The occupant deceleration and the occupant's chest and head rotational acceleration are used as injury criteria. It is shown from the numerical simulations that the occupant behaviour can be captured and analysed quickly and accurately. Furthermore, it is shown that the VDCS can affect the crash characteristics positively and the occupant safety is improved.

INTRODUCTION

The most well-known pre-collision method is the advance driver assistant systems (ADAS). The aim of ADAS is to mitigate and avoid vehicle frontal collisions. The main idea of ADAS is to collect data from the road (i.e. traffic lights, other cars distances and velocities, obstacles, etc.) and transfer this information to the driver, warn the driver in danger situations and aide the driver actively in imminent collision. There are different actions may be taken when these systems detect that the collision is unavoidable. For example, the brake assistant system (BAS) [1] and the collision mitigation brake system (CMBS) [2] were used to activate the braking instantly based on the behaviour characteristics of the driver, and relative position from the most dangerous other object for the moment.

During frontal vehicle collision, it is found that the vehicle body pitch and drop play an important role in driver's neck and head injury [3, 4]. Vehicle body pitch and drop have normally been experienced in frontal crash tests. Chang et al. [3] investigated frame deformation upon full-frontal impact using a finite element (FE) method and discussed the cause and counter-measures design regarding vehicle body pitch and drop. It was found that downward bending generated from the geometric offsets of the frame rails in the vertical direction during a crash is the key feature of the pitching of the vehicle body.

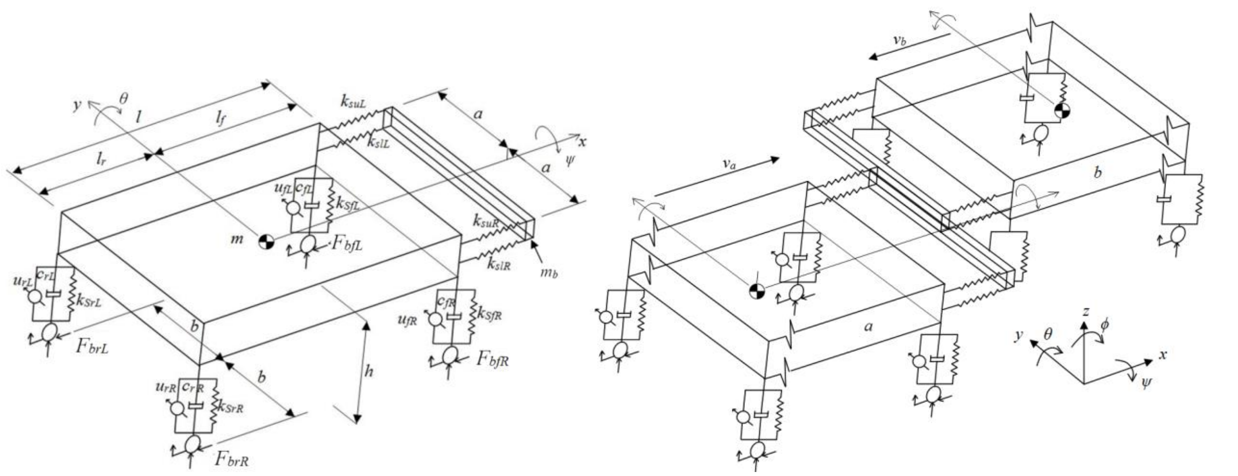
Using mathematical models in crash simulation is useful at the first design concept because rapid analysis is required at this stage. In addition, the well-known advantage of mathematical modelling provides a quick simulation analysis compared with FE models. Vehicle crash mathematical modelling is used to represent the vehicle front structure [5]. Also, other analyses and simulations of vehicle-to-barrier impact using a simple mass spring model were established by [6]. A simple lumped-parameter model is used, discussed the applicability of providing variable energy-absorbing properties as a function of the impact speed [7]. The occupant can also be modelled mathematically as a one-mass model [8], a two-mass model [9], a three-mass mode [10] or a multi-mass model [11]. In the most of these studies, the researchers claimed that simple occupant mathematical models can obtain usefully similar results to sophisticated analytical and experimental work.

Vehicle dynamics control systems (VDCS) play an important role in improving vehicle stability, ride characteristics, and passenger safety. On the other hand, the effect of VDCS on vehicle crashworthiness and collision mitigation is considered in several studies. The influence of the braking force on vehicle impact dynamics in low-speed rear-end collisions was studied [12] and this confirmed that the braking force was not negligible in high-quality simulations of vehicle impact dynamics at low speed. The effect of vehicle braking and anti-pitch control systems on the crash routine have been investigated by Hogan [13], who also investigated the possibility of using VDCS to improve vehicle collision performance in full and offset frontal vehicle to barrier collision.

However, there are no studies have been found that investigate the effect of VDCS on the occupant safety. From the existing literature, it is clear that research work done on the effect of VDCS on the occupant safety is rare. Hereafter the current study is fulfilled to determine the occupant response in offset crash scenario with different cases of VDCS. To accomplish this study, a mathematical multi-body occupant model has been developed.

THE NEW VEHICLE DYNAMICS/CRASH MATHEMATICAL MODELLING FOR PRIMARY IMPACT

The primary impact indicates the collision between the front-end structure of the vehicle and an obstacle (another vehicle in this paper). This section describes a 6-DOF vehicle dynamics/crash-mathematical model, shown in Figure 1, which has been former developed by the author [14], for one vehicle and in case of a crash scenario between the two vehicles, where subscript *a* denotes vehicle (a) which is equipped with the VDCS and a subscript *b* denotes vehicle (b) which is used in a free rolling case for all crash scenarios. This model has been used to study the effect of vehicle dynamics control systems on vehicle collision mitigation.



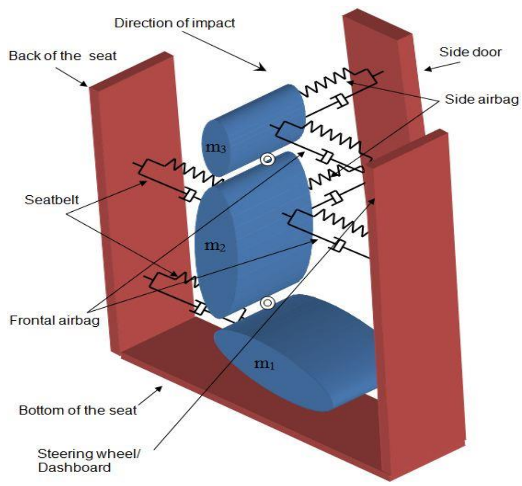
6-DOF one vehicle model ***vehicle-to-vehicle offset crash scenario***

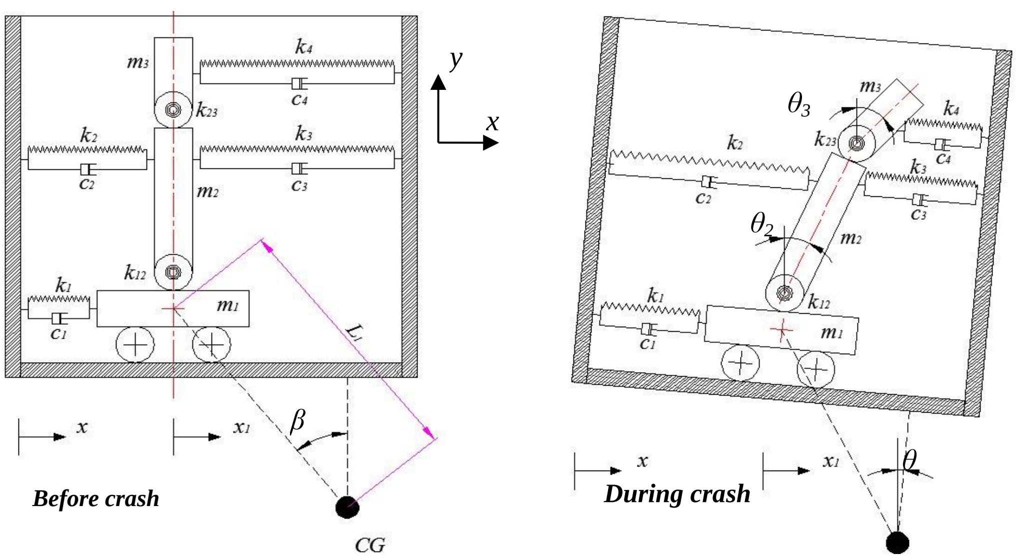
Figure 1. Vehicle dynamics/crash-mathematical model

As shown in Figure 1, four spring/damper units are used to represent the conventional vehicle suspension system. Each unit has a spring stiffness k_S and damping coefficient c. The subscripts *f*, *r*, *R* and *L* denote the front wheels, real wheels, right wheels and left wheels, respectively. The ASC system is co-simulated with the conventional suspension system to add or subtract an active force element u, and the ABS is co-simulated with the mathematical model using a simple wheel model to generate the braking force F_b. To represent the front-end structure of the vehicle, four nonlinear springs with stiffness k_s are proposed. Two springs represent the upper members (rails) and two springs represent the lower members of the vehicle frontal structure. The subscripts u denotes the upper rails while the subscript *l* denotes the lower rails. The bumper of the vehicle is represented by a lumped mass m_b and it has only a rotational motion about the point of collision. The equations of motion and control systems have been described in details in a previous study by the author [14] to predict the vehicle deceleration, pitching angle and acceleration, and yawing angle and acceleration. These outputs from the vehicle model are used as input data for the occupant model.

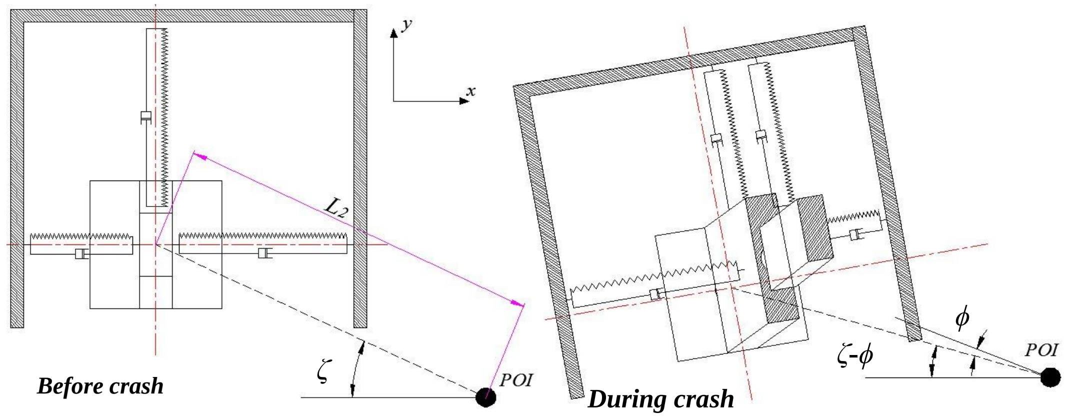
MULTI-BODY OCCUPANT MODEL (SECONDARY IMPACT)

The occupant biodynamic model, with its different views before and after the crash shown in Figure 2, is developed to evaluate the occupant kinematic behaviour during the secondary impact. The secondary impact is the interaction between the occupant and the restraint system and/or the vehicle interior due to vehicle collisions. The human body model consists of three bodies, with masses m_1, m_2 and m_3. The first body (pelvis), with mass m_1, represents the legs and the pelvic area of the occupant and it is considered to have a translation motion in the longitudinal direction and rotation motions (pitching, rolling and yawing) with the vehicle body. The second body (chest), with mass m_2, represents the occupant's abdominal area, the thorax area and the arms and it is considered to have a translation motion in the longitudinal direction and rotation motion around the pivot between the pelvis and the chest bodies (pivot 1). The third body (head), with mass m_3, represents the head and neck of the occupant and it is considered to have a translation motion in the longitudinal direction and rotation motion around the pivot between the chest and the head (pivot 2). A rotational coil spring is proposed at each pivot to represent the joint stiffness between the pelvis and the chest areas and between the chest and the head areas, respectively. The seatbelt is represented by two linear spring-damper units between the compartment and the occupant; the frontal and side airbags are represented by tow linear spring-damper units for each one.

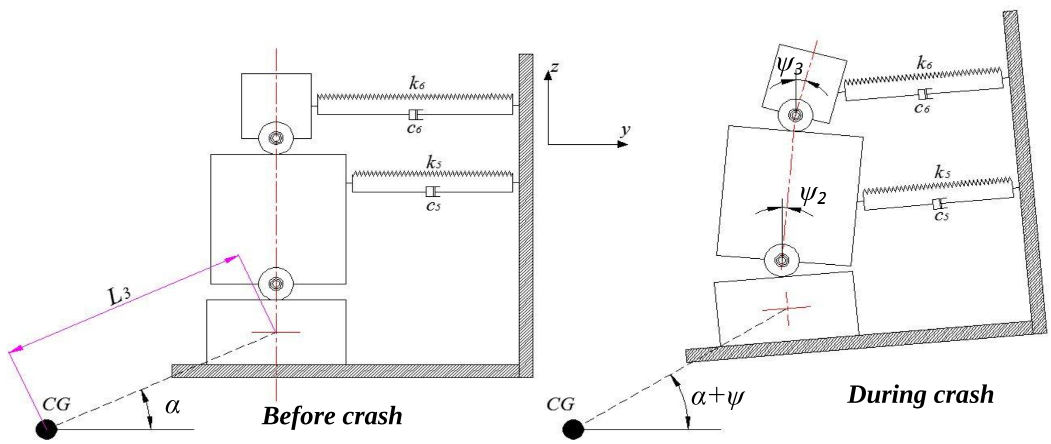




Side view of the occupant model



Top view of the occupant model (POI: Point of Impact)



Frontal view of the occupant model

Figure 2. Multi-body occupant model (secondary impact) and its different views before and during the crash

Equation of Motion (EOM) of the Human Body Model

Due to the complexity of obtaining the equation of motions directly from the system, Lagrange's equations have been used to describe the general motions of the multi-body human model as follows:

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{x}_1}\right)-\frac{\partial E}{\partial x_1}+\frac{\partial V}{\partial x_1}+\frac{\partial D}{\partial \dot{x}_1}=0 \tag{1}$$

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\theta}_2}\right)-\frac{\partial E}{\partial \theta_2}+\frac{\partial V}{\partial \theta_2}+\frac{\partial D}{\partial \dot{\theta}_2}=0 \tag{2}$$

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\theta}_3}\right)-\frac{\partial E}{\partial \theta_3}+\frac{\partial V}{\partial \theta_3}+\frac{\partial D}{\partial \dot{\theta}_3}=0 \tag{3}$$

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\psi}_2}\right)-\frac{\partial E}{\partial \psi_2}+\frac{\partial V}{\partial \psi_2}+\frac{\partial D}{\partial \dot{\psi}_2}=0 \tag{4}$$

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\psi}_3}\right)-\frac{\partial E}{\partial \psi_3}+\frac{\partial V}{\partial \psi_3}+\frac{\partial D}{\partial \dot{\psi}_3}=0 \tag{5}$$

where E, V and D are the kinetic energy, potential energy and the Rayleigh dissipation function of the system, respectively. x_1, θ_2, θ_3, ψ_2 and ψ_3 are the longitudinal movement of the occupant's pelvis, the rotational angle of the occupant's chest about (y) axis, the rotational angle of the occupant's head about (y) axis, the rotational angle of the occupant's pelvis about (x) axis and the rotational angle of the occupant's head about (x) axis, respectively. $\dot{x}_1$, $\dot{\theta}_2$, $\dot{\theta}_3$, $\dot{\psi}_2$ and $\dot{\psi}_3$ are their velocities, respectively. To get the components of the equations 1, 2, 3, 4 and 5, the differentiations of the kinetic energy, potential energy, and Rayleigh dissipation function are determined. To solve these equations, they have been put in an integratable form and then rewritten in a matrix form. After that, different occupant's bodies responses (x_1, θ_2, θ_3, ψ_2 and ψ_3) can be determined based on the input data from the vehicle model by solving the equations numerically.

NUMERICAL SIMULATIONS OF VEHICLE-TO-VEHICLE OFFSET-COLLISION SCENARIO

Two different cases of VDCS are investigated in this section and their associated results are compared with the free rolling case scenario. These different VDCS cases are described as follows:

Case 1: Free rolling: - in this case the vehicle collides with a barrier/vehicle without applying any types of control.
Case 2: Anti-lock braking system (ABS): - in this case the anti-lock braking system is applied before and during the collision.
Case 6: Anti-lock braking system alongside under-pitch control system (ABS + UPC): - in this case, the vehicle is taken a reverse pitching angle before crash using an ASC system.

The injury criteria in this paper have been taken as occupant's pelvis deceleration, occupant's chest rotational acceleration, and head rotational acceleration. The vehicle output data (deceleration and pitching and yawing acceleration) due to the collision [14] are transferred to the occupant as a sudden deceleration to all the body. The following data is used in the numerical simulation: m_1 = 26.68 kg, m_2 = 46.06 kg, m_3 = 5.52 kg, k_{R12} = 280 Nm/rad, k_{R23} = 200 Nm/rad, l_2 = 0.427 m, l_3 = 0.24 m [10]. The total stiffness of the two seatbelt springs is 98.1 kN/m with a damping coefficient of 20% [8], and then it distributed between the upper and lower seatbelt springs by ratio of 2:3, respectively [15]. Airbag's spring stiffness is 5 kN/m and the damping coefficient is 20%. The slacks of the seatbelt springs are assumed zero, and the slack of the airbag is 0.05 m.

For the occupant's pelvis relative displacement for vehicle (a), it is shown that it increases forward to reach its maximum position and then returns due to the lower seatbelt springs. It is observed that there are insignificant differences between the values of the maximum relative displacement of the occupant's pelvis in the different cases of VDCS. Regarding to the lower-body deceleration of the vehicle (a), it is shown that it increases during the collision to reach its maximum values at the end of impact and then reduces after the effect of collision is ended. There is a sudden decrease of the deceleration at the end of collision, this is due to the reverse effect of the braking force when the vehicle changes its direction and starts to move backward. It is observed that the maximum deceleration is almost the same for all cases with very small differences. These small differences mean that the VDCS do have an insignificant effect on the pelvis relative displacement and deceleration.

The rotation angle of the occupant's chest about y axis for all cases of vehicle (a) is shown in Figure 3. The occupant's chest starts the collision with different rotational angles according to each case of the VDCS. The occupant takes this angle in the period of 1.5 sec prior collisions when the VDCS is applied. After that, the rotational angle of the occupant's chest remains constant for about 0.03 sec, then it increased to reach its maximum value after the end of the collision. The maximum rotation angle is observed in case 2, while the minimum one is observed in case 3 (ABS + UPC). The rotational acceleration about y axis of the occupant's chest is captured. The chest rotational acceleration increases gradually to reach its maximum positive value and then reduces to reach its maximum negative value. The maximum positive rotational acceleration is monitored in case 1 and the minimum one occurred in case 2, while the maximum negative rotational acceleration is shown in case 3 and the minimum is in case 2.

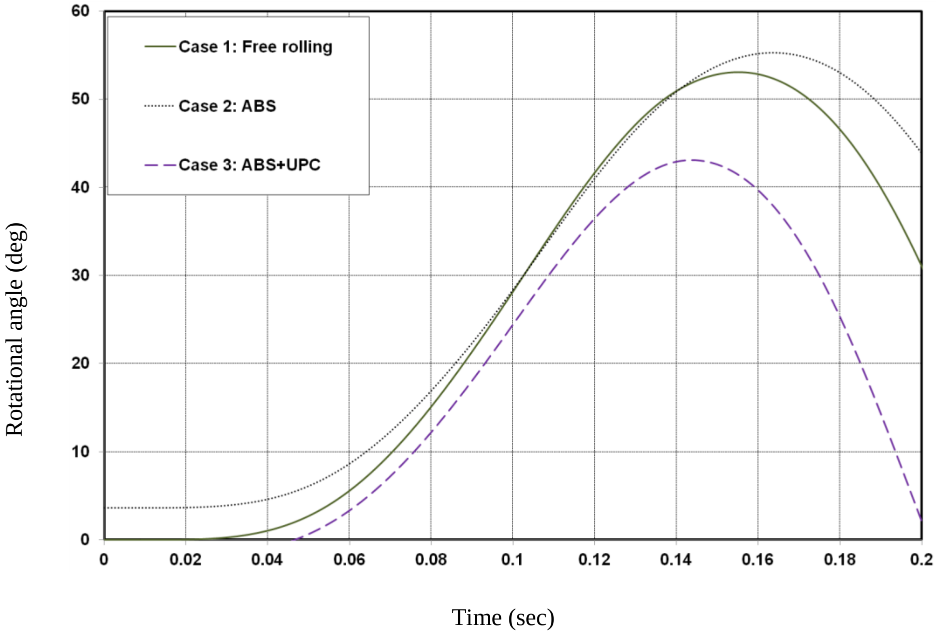


Figure 3. **Rotational angle of the occupant's chest about y axis (Offset frontal vehicle-to-vehicle impact), vehicle (a)**

The rotation angle of the occupant's head about y axis is depicted in Figure 4. The head rotation angle increases rapidly for a period of time, which occurred during the increase of the chest rotation. Then, it increases fast due to the return of the occupant's chest to reach its peak value (maximum value). The peak value of the head rotational angle is observed in case 2, while the minimum one is detected in case 3. The rotational acceleration of the occupant's head is also shown, the acceleration increases with a different manner according to each case to reach its maximum value. These maximum values occurred in different time related to each case. In other words, the maximum acceleration in cases 1 and 3 occurs approximately at 0.07 sec, while in case 2 it occurs approximately at 0.08 sec. The minimum negative acceleration is observed in cases 2, while the maximum negative values are seen in cases 1 and 3.

The rotation angle about x axis of the occupant's chest for all cases of vehicle (a) is depicted in Figure 5. When the occupant's chest reaches its maximum rotational angle, it stays in this position for a period of time while the vehicle rotates around the point of impact. The maximum rotation angle is observed in case 1 (free rolling) while the minimum angle is observed in cases 3 (ABS + UPC). The rotational acceleration of the occupant's chest about x axis for all cases of vehicle (a) is obtained. There are three sudden changes in the acceleration during collision. The first one is due to the activation of the side airbag, while the second one is due to the reverse braking force. The third sudden change of the chest acceleration is due to the deactivation of the vehicle's front-end springs, which causes a sudden decrease of the vehicle pitching, yawing and rolling. The maximum positive rotational acceleration of the occupant's chest about x axis is observed in cases 1, while the minimum value occurs in case 3. The maximum negative rotational acceleration happens in case 1 and the minimum is observed in case 3. These negative acceleration values occur due to the force generated by the lower spring-damper system of the side airbag.

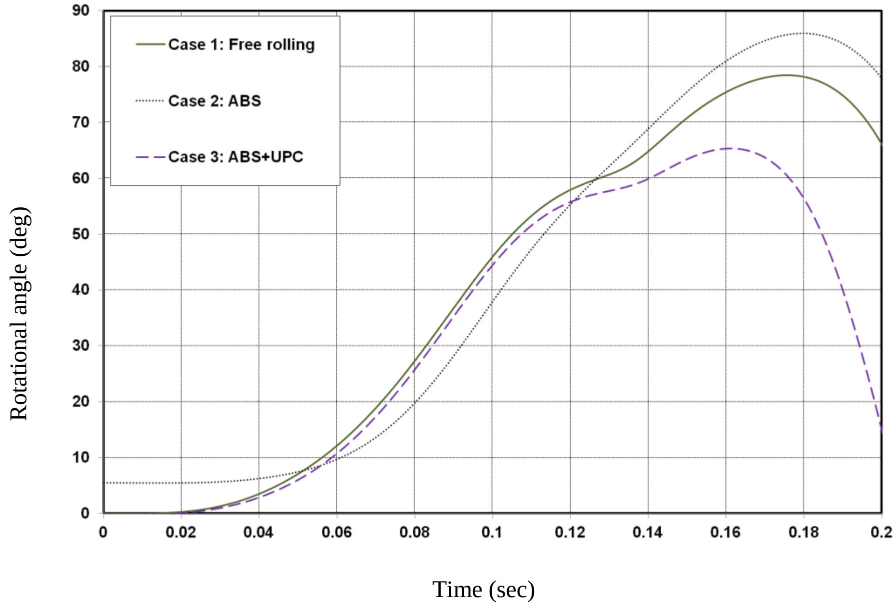


Figure 4. Rotational angle of the occupant's head about y axis (Offset frontal vehicle-to-vehicle impact), vehicle (a)

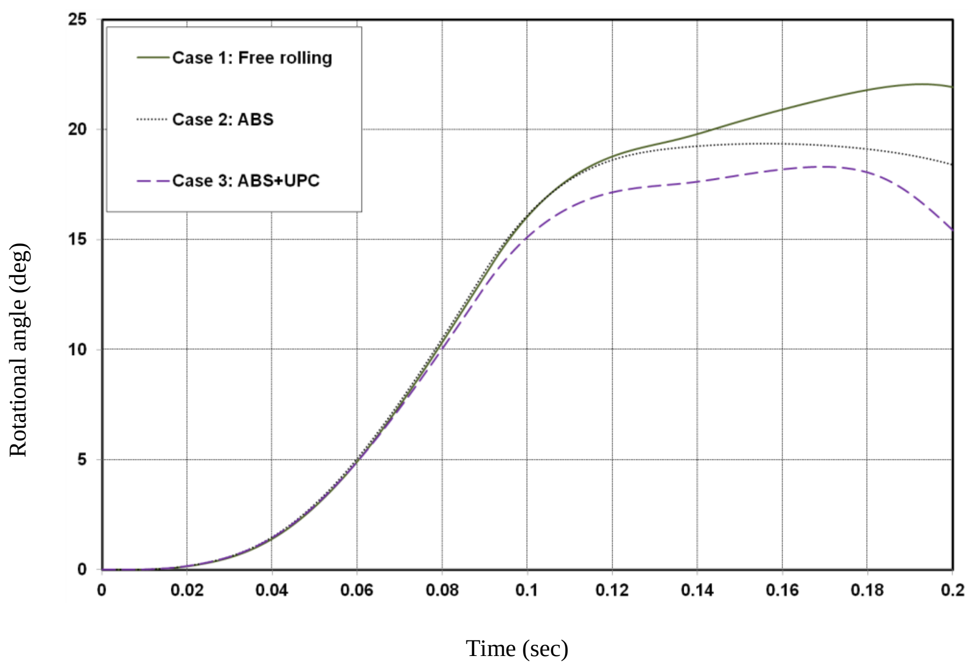


Figure 5. Rotational angle of the occupant's chest about x axis (Offset frontal vehicle-to-vehicle impact), vehicle (a)

The rotation angle about x axis of the occupant's head for the vehicle (a) is shown in Figure 6. At the beginning of the collision, while the chest takes a positive acceleration and starts rotating towards the vehicle's side door, the head takes a different negative small rotation value related to each case, all these values are close to 5 deg. The positive maximum value of the head rotational angle is observed in case 3, while the minimum peak angle is seen in case 2. The rotational acceleration about x axis of the occupant's head in all cases has been gained. The effect of the reverse braking force is observed at the end of the collision. The maximum positive acceleration (in the period from 0.06 to 0.1 sec) is almost the same for all cases, while the maximum negative acceleration (in the period from 0.1 to 0.16 sec), caused by the side airbag force, is observed in case 1 with relatively a higher value. The minimum negative acceleration is detected in case 2.

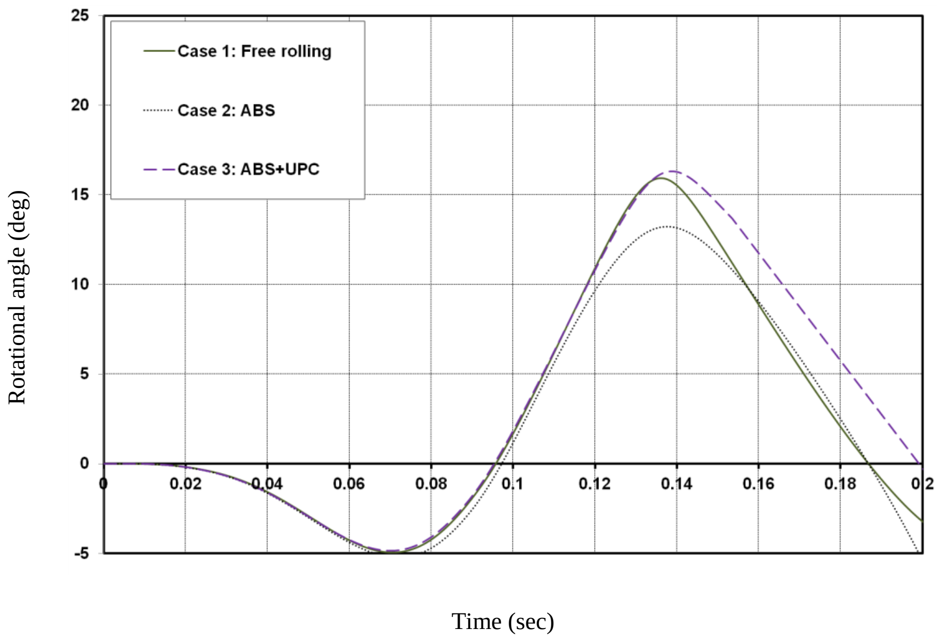


Figure 6. Rotational angle of the occupant's head about x axis (Offset frontal vehicle-to-vehicle impact), vehicle (a)

The occupant behaviour of the occupant of the vehicle (b) is also captured for all cases of the VDCS. It is shown that applying the VDCS for vehicle (a) has insignificant effect on the other vehicle.
Related to the occupant injury criteria, the occupant's head rotational accelerations appeared to be the major cause of strain-induced brain injury which it contributed to more than 80% of the brain strain and the peak amplitude of rotational acceleration must not exceed 9.4 krad/s^2 (538.5 kdeg/s^2) [16]. The results show some improvement in the occupant injury criteria, which makes the crash event more survivable. Use of under pitch technique (case 3) can help reduce the chest and head rotation angle, and head rotational acceleration. The VDCS affects the occupant's behaviour with different ways related to the applied case, and it can be seen that the applied of frontal UPC alongside ABS (case 3) can be taken as the best case due to its effect on the occupant's head (the most important part of the occupant's body). The future study, as extensions to this work, will be focused on the optimization of using different integrated VDCS.

CONCLUSIONS

A multi-body occupant mathematical model has been developed to study the effect of VDCS on the occupant dynamic response during vehicle collision. Different cases of the VDCS have been investigated in case of vehicle-to-vehicle frontal offset collision. The results obtained from a previous vehicle model have been used as the input data for the occupant model. The results show that the effect of the VDCS is quite minimal in terms of occupant relative displacement and deceleration. However, there are a significant effect on the rotations angle and acceleration of the occupant chest and head, which are greatly enhanced.

ACKNOWLEDGMENT

The authors would like to thank the Egyptian Government and the Faculty of Engineering, Ain Shams University for supporting this research.

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